Ocean zoning for conservation, fisheries and marine renewable energy: assessing trade-offs and co-location opportunities

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Short title

Assessing trade-offs in ocean zoning

Keywords

Marine protected areas, fisheries management, off-shore wind farms, tidal energy, marine spatial planning

Abstract

Oceans, particularly coastal areas, are getting busier and within this increasingly human-dominated seascape, marine biodiversity continues to decline. Attempts to maintain and restore marine biodiversity are becoming more spatial, principally through the designation of marine protected areas (MPAs). MPAs compete for space with other uses, and the emergence of new industries, such as marine renewable energy generation, will increase competition for space. Decision makers require guidance on how to zone the ocean to conserve biodiversity, mitigate conflict and accommodate multiple uses. Here we used empirical data and freely available planning software to identified priority areas for multiple ocean zones, which incorporate goals for biodiversity conservation, two types of renewable energy, and three types of fishing. We developed an approached to evaluate trade-offs between industries and we investigated the impacts of co-locating some fishing activities within renewable energy sites. We observed non-linear trade-offs between industries. We also found that different subsectors within those industries experienced very different trade-off curves. Incorporating co-location resulted in significant reductions in cost to the fishing industry, including fisheries that were not co-located. Co-location also altered the optimal location of renewable energy zones with planning solutions. Our findings have broad implications for ocean zoning and marine spatial planning. In particular, they highlight the need to include industry subsectors when assessing trade-offs and they stress the importance of considering co-location opportunities from the outset. Our research reinforces the need for multi-industry ocean-zoning and demonstrates how it can be undertaken within the framework of strategic conservation planning.

1.Introduction

Unsustainable use of the marine environment has led to rapid declines in biodiversity (Airoldi and Beck, 2007; Sala and Knowlton, 2006; Worm et al., 2006). Efforts to restore and maintain marine biodiversity are focused increasingly on spatial approaches; over the past two decades there has been a surge of mandates for the establishment of marine protected areas (MPAs) and MPA designation rates have increased rapidly (Pita et al., 2011). MPAs are designated for a variety of reasons, including biodiversity conservation (Agardy, 1999; Jones, 1995) and fisheries management (DEFRA, 2005; Gell and Roberts, 2003; Halpern et al., 2010). There are many types of MPAs and the level of protection varies, from highly protected marine reserves to areas where all activities are accommodated at managed levels. Fishing is the most common activity restricted or excluded from MPAs, creating conflict between the conservation and fishing communities. Consequently, most MPA planning processes seek to minimize this conflict (e.g. Gleason *et al*. (2010), Yates and Schoeman (2014)). However, as oceans get busier and new industries emerge, both conservation and fisheries will face growing competition for space, and marine planners will have to deal with a wider range of spatial conflicts.

Ocean zoning, a component of marine spatial planning, has been proposed to accommodate multiple conflicting and compatible uses of the ocean (Crowder et al., 2006). Ocean zoning is the process of dividing a marine region into zones and within those zones, regulating uses to achieve specific purposes (Courtney and Wiggin, 2002). General frameworks and guides for ocean zoning exist, and are typically part of broader marine spatial planning guidelines (Agardy, 2010; Day, 2002; Ehler and Dourvere, 2009; Foley et al., 2010; Halpern et al., 2008). As part of these, spatial analyses must be conducted to identify priority areas for the multiple zones - but how? A range of spatial prioritization approaches has been suggested; however, these approaches are of limited focus or cannot optimize benefits for a range of activities. For example, zoning approaches based on multi-criterion analysis (Bruce and Eliot, 2006; Portman, 2007; Villa et al., 2002) or trade-off analyses have been demonstrated (White *et al*. 2012), but ignore important principles of protected-area design (Margules and Pressey, 2000; Wilson et al., 2009). Other approaches, based on systematic conservation planning, have been applied but are focused on a narrow suite of human priorities, namely conservation and fishing (Grantham et al., 2013; Klein et al., 2010). In reality, countries need to allocate zones for a broader suite of activities.

The rapid expansion of the marine renewable energy industry, driven by nations' commitments to reducing greenhouse gas emissions, has been a catalyst for the progression of ocean zoning and marine spatial planning (Douvere and Ehler, 2009; Firestone and Kempton, 2007). The marine renewable energy industry expansion is likely not only to continue, but to accelerate. In the UK, for example, offshore wind energy capacity increased by 37% between 2010 and 2011, to 1.8 gigawatts, and is expected to increase to 18 gigawatts by 2020 (Hooper and Austen, 2014). Nations require systematic and transparent approaches to help make decisions about the locations of future offshore energy developments, as well as other emerging ocean uses, whilst balancing competing uses, including conservation and fishing.

Here, we build upon previous zoning approaches focused on zoning for conservation and fishing (Grantham et al., 2013; Klein et al., 2010) to also include zones for wind and tidal energy. We develop an ocean zoning approach to optimize space allocation for conservation, fishing, and offshore marine renewable energy generation, and apply it to Northern Ireland, a country that is expanding its existing MPA network and developing its renewable marine energy generation infrastructure. We identify multiple zoning configurations and evaluate the trade-offs between conservation, fishing, and renewable energy. We also evaluated the impact of co-locating fishing using static gear (pot fishing) and renewable energy on both the cost and spatial configuration of zones. Our zoning approach and trade-off analysis will help make decisions about ocean zoning more systematic, transparent, and repeatable, and can be used to identify cost effective priorities for any number of ocean uses (e.g. aquaculture, mining) around the world.

2. Materials and Methods

2.1 Study Area and policy context

Our study area was Northern Ireland's territorial waters, up to 12 nautical miles offshore, covering an area roughly 4600 km^2. Within these waters, the three main fisheries are *Nephrops* (trawl), scallops (dredge) and pot fishing (creels, mainly for lobsters and crabs). There are currently no offshore wind farms in place or under development, and there is one experimental tidal energy turbine, in Strangford Lough. There are six existing MPAs (see supplementary figure S1), designated, among other classifications, as Special Areas of Conservation under European Legislation(EC, 2007).

Northern Ireland marine management is governed by a complex hierarchy of legislation and policy, including: International conventions, European directives, National UK legislation, and local Northern Ireland specific legislation (Yates et al., 2013). Recent legislative and policy developments have placed an increased emphasis on MPAs and spatial management, and the Northern Ireland is committed to expanding the existing network of MPAs to develop a more coherent, representative network (Yates et al., 2013). The main driver for expanding the existing MPA network is the need to conserve biodiversity. However, there is also a growing desire, both top-down, from national policy makers, and bottom-up, from local fishers, for the use of MPAs as a tool for fisheries management (Yates, 2014; DEFRA 2005). The newly passed Northern Ireland Marine Act has provided the Assembly with the necessary powers to both expand the existing MPA network and to develop a comprehensive Marine Spatial Plan (The Northern Ireland Assembly 2013a).

In addition to the increased demand for space for MPAs, there is also the emerging demand for space for marine renewable energy generation. The UK is committed to reducing its carbon emissions (DTI, 2007), and under the governments Renewables Obligation at least 9.7% of Northern Ireland's electricity must be generated through renewable sources (The

Northern Ireland Assembly 2013b). This percentage is anticipated to rise steeply each year until the UK Government's target, 20% by 2020, is met. In Northern Ireland much of the focus is on developing tidal energy and off-shore wind farms. A series of potential development areas have already been identified (Supplementary materials S1) by the Northern Ireland Department of Enterprise, Trade and Investment in their regional locational guidance (DETI, 2011).

2.2 Data

2.2.1 Biodiversity features

We targeted a total of 60 biodiversity conservation features for inclusion into MPAs under all scenarios. These consisted of 45 habitats, two foundation species, two spawning areas, five nursery grounds, and six depth zones (Supplementary materials S2). Data were provided by the Northern Ireland Department of the Environment (DOE) and the UK Joint Nature Conservation Committee (JNCC). Along with all other data in this study, biodiversity data were managed within the Geographical Information System (GIS) ArcGIS 10.0.

2.2.2 Fishing

We used fisheries data derived from Spatial Access Priority Mapping (SAPM) interviews with 103 Northern Irish fishers, all of whom were vessel skippers and/or owners. Interviews were conducted in 2012 (Yates and Schoeman, 2013). Respondents mapped their priority area(s) directly into the GIS, identified which fishery each area was for and assigned relative importance to each area, such that total importance value for each respondent was 100. Respondents also provided details about their vessel, including the total number of crew. The Spatial Access Priority (SAP km^{-2}) of each area was then calculated as follows:

$$SAP_x = \frac{C_x \times I_x}{A_x} \quad (1)$$

Where x is a given area mapped by a respondent. C is the number of crew on that respondent's vessel, I is the importance value assigned by the respondent for that area, and A is number of square kilometres the area covered.

Individual SAPs were multiplied by a weighting to account for differences in the proportion of respondents obtained from the various sections of the fishing community and then summed generate maps that represent the whole fleet (equation 2). Vessels were divided into eight categories, based on gear type and vessel length (Yates and Schoeman 2013). The average number of crew for each of these categories was calculated from the sample data (obtained during the 103 interviews). Using a list of all registered vessels, an estimate of the total number of crew for each port/gear type/vessel length combination was calculated. The number of estimated crew for each port/gear/vessel length combination (EC) was divided by total number of crew actually in the sample (SC) for that given port/gear/vessel length combination. This was then used to weight the individual SAPs.

$$\sum_{i=1}^{n} SAP = \left(\frac{C_i \times I_i}{A_i}\right) \times \left(\frac{EC_i}{SC_i}\right) \quad (2)$$

For more detailed SAPM methodology, including worked examples, see Yates and Schoeman, 2013.

SAPM generates quantitative spatial data on fishers' perceived value for the ocean, without the need for often unavailable revenue or landings data. SAP data can be used as a surrogate cost layer, with SAP being fishing value, and the displacement of SAP, due to restricted access, being the cost of that restriction to the fishery(ies) (Yates and Schoeman 2014). SAP data could be combined with fisheries revenue and/or landings data, if available and desired, to create a monetary cost layer. For our study site, however, these additional data were not available.

In addition to mapping the spatial access priorities of the fleet as a whole, SAPM can also be used to derive individual data sets for each fishery. We used the SAP data for each of the three main fisheries (*Nephrops*, scallops, pots) as features and targeted a percentage of each to be maintained within fishable areas (Table 1).

Scallop fishers in Northern Ireland have expressed a desire for scallop stock management areas that would prohibit all mobile fishing gear and benthos development (Yates, 2014). Thus, in addition to targeting a percentage of scallop fishers' SAP to be maintained within fishable areas, we targeted a percentage of scallop fishing grounds to be incorporated into MPAs. Ideally the siting of these areas would be based on data on the distribution of scallops. However, these data were not available, so we used fishing grounds as a surrogate. We identified the main scallop-fishing grounds using data obtained from interviews with fishers (Yates and Schoeman, 2013). We overlaid locations identified by fishers as being scallop-fishing grounds within the GIS and we classified any area that was identified by at least three fishers a main fishing ground.

We obtained data on the location of aquaculture sites from the Agri-food and Bio-sciences Institute, in Northern Ireland. We designated existing aquaculture sites as unsuitable for incorporation into other zones and as such were locked into a separate aquaculture zone.

2.2.3 Renewable Energy

We obtained data on potential marine renewable energy development areas from the Northern Ireland Department of Enterprise Trade and Investment (DETI). These were areas that had already been assessed by DETI, in conjunction with regulators and industry, as suitable for either tidal or wind-farm development. DETI identified two potential areas for wind-farm development (1400 km^2), and five potential areas identified for tidal energy generation (230 km^2) (Supplementary figure S1). The Northern Ireland Government is aiming to lease around 30% of the total potential area (DETI, pers. comm). No data were available on the spatial variation in value (e.g. expected revenue) of these areas, and so targets for wind and tidal energy were set as a percentage of the total area.

2.3 Zoning

We divided the study area into 5169 square planning units. The planning units were typically 1 km^2, but their size varied at the land and edge of study region. We used the decision support tool Marxan with Zones (Watts *et al*. 2009) to identify cost-effective solutions to the zoning problem. Marxan with Zones uses a simulated annealing algorithm to solve a minimum set problem, namely how to achieve given targets at the lowest possible cost. In doing so, Marxan with Zones aims to minimize the total cost of the overall zoning plan, subject to the constraint that zone specific targets are achieved. Activities can be restricted to certain zones and zones can be restricted to certain spatial distributions. The user can specify how much each zone will contribute to meeting the various targets (zone effectiveness) and how much of each target must be met in each zone (zone target). We produced 200 solutions for each scenario, and considered the 'best solution' the one with lowest overall cost.

We defined cost as lost fishing value (total SAP displaced). Currently, fishers are the main commercial users of Northern Ireland's territorial waters, and fishers are also the group most likely to be impacted by spatial restrictions. In order to minimize negative socio-economic impacts and reduce conflicts associated with possible zoning solutions, we minimised the total SAP displacement. Thus the cost of placing a planning unit into a particular zone is the fishing value (total SAP) of all the fisheries that are excluded from it (Table 1).

We developed a multi-industry zoning scenario, which optimized zone configuration when simultaneously planning for conservation, fisheries and renewable energy. It contained seven zones: three MPA zones, two renewable energy zones, an open fishing zone and an aquaculture zone (Table 1). We set initial conservation targets at 15% of each biodiversity feature to be contained within the three MPA zones (reserve, conservation zone and scallop management zone) and at least 5% of each biodiversity feature within reserves. We considered these to be plausible targets, given that Northern Ireland is already committed to protecting 10% of its marine waters within MPAs, under the Convention of Biological Diversity (United Nations, 1992), and that The World Parks Congress calls for between 20 – 30 % of the sea in highly protected marine reserves (World Resources Institute, 2003).

For each of the three main fisheries we set an initial target of 80% of their total value (SAP) to remain accessible (in fishable areas), reflecting both the importance of these fisheries and the inevitability of some displacement. To meet the objectives of scallop fishers, we targeted 10% of the main scallop fishing grounds for inclusion across the three MPA zones, with a specific target of at least 5% to be incorporated with the scallop management zones. We considered this a realistic balance between general recommendations (Gell and Roberts, 2003; Roberts and Hawkins, 2000) and the immediate needs of local scallop fishers, who have requested MPAs for scallop fishery management, but also do not want to lose too much of their grounds (pers.comm). Initial renewable energy targets were set at 30% of the total suitable area, based on government expectations. Pre-existing MPAs, which currently restrict only dredging and trawling, were restricted to one of the three MPA zones.

We explored the trade-offs between representing biodiversity features, reducing the impacts on fisheries, and providing space for renewable energy development, at a range of target levels. We incrementally increased the fisheries target from the original 80%, kept targets for conservation zones constant (Table 1), and observed the extent to which the renewable energy target could be met. We then incrementally increased the renewable energy target from 30%, kept targets for conservation zones constant, and observed the extent to which the fisheries target could be met. We repeated this analysis twice, where 20 and 25% of each conservation feature was included within one of the three MPA zones. The targets for the scallop fishery, scallop management zones and reserve zones were held constant at levels (10%, 5% and 5% respectively).

We next investigated the impact of co-location (allowing concurrent activities in time or space) of marine renewable energy and fishing on the cost (displaced SAP) of planning solutions for the whole fleet and for each of the three main fisheries. Whilst the logistics of dredge and trawl fishing (size of the vessels, nature of the gear/sea bed interaction etc.) make co-location with renewable energy generation sites unlikely, there has been much discussion about the possible benefits of co-location of renewable energy sites with static gear (e.g.(Hooper and Austen 2014)). Therefore we developed a set of scenarios in which some pot fishing occurred within renewable energy zones. We tested two levels of co-location, where either 25 or 50% of the original pot fishing value (SAP) was maintained in areas zoned for renewable energy. We did this by modifying both the zone effectiveness, such that renewable energy zones had an effectiveness of 0.25 or 0.5 for the pot fishing target instead of 0, and by reducing the cost, such that the cost of planning units incorporated into renewable energy zones was reduced by either 25 or 50% of their original pot fishing value (SAP). We also examined the impact of co-location on the selection of planning units within renewable energy zones and on the trade-offs between the industries, at the 25% co-location level.

3. Results

3.1 Trade-offs between industries

As we increased the target for fisheries, the extent to which the initial renewable energy target could be met, and thus the amount of area allocated to renewable energy zones, declined non-linearly, with noticeably different effects on the two renewable energy sectors (Figure 1, A & B). Once fishing targets exceeded 83%, the percentage area allocated to the wind-farm zone experienced a linear decline. However, the tidal energy zone had a very distinct trade-off point, remaining almost entirely unaffected until the fisheries target exceeded 91%. For each target variation, all conservation targets were achieved.

As we increased the target for renewable energy, the extent to which the initial target for fisheries could be met, and thus percentage of fishing value that could be maintained in fishable zones, declined (Figure 1, C). Again, there were substantial differences in how the increasing target for renewable energy affected different sectors within the fishing industry (Figure 1, D). Analysis did not precede beyond renewable energy targets of 81%, as past that point it was no longer possible to achieve the conservation targets.

At higher conservation target levels (20 & 25%) the trade-offs between the industries followed the same overall pattern, only with corresponding reductions in the proportion of the industry targets that were attainable. At a conservation target of 25%, for example, the maximum obtainable fisheries target was 89%, compared to 94% when the conservation target was 15%. By combining all these scenarios we generated a better understanding of the trade-offs between possible target levels for conservation, fisheries and renewable energy (Supplementary figure S3).

3.2 Co-location

Planning scenarios that allowed for co-location of either 25% or 50% pot fishing within renewable energy sites significantly reduced the cost of solutions to the overall fishing industry ($P < 0.0005$, d.f = 29, F = 865), and to the pot fishing sector in particular ($P < 0.0005$, d.f = 29, F = 1869). The cost for the overall fishing industry reduced by up to 15% and the pot sector reduce by up to 57 % (Figure 2). Whilst the biggest cost reduction was found when going from 0 to 25% co-location, post-hoc tests (Tukey's Honestly Significant Differences) demonstrated significant difference ($P < 0.005$) between all three levels (0, 25%, 50%), for both the overall fishing industry and the pot fishing sector.

Interestingly, allowing co-location of pot-fishing within renewable energy sites also significantly reduced the cost of planning solutions for fisheries other than pot fishing. Scenarios that included co-location had an 11 % lower mean cost for the scallop-fishery ($P < 0.0005$, d.f = 29, F = 306) and for the *Nephrops* fishery, the mean solution cost was reduced by 9% ($P < 0.0005$, d.f = 29, F = 284). Co-location also impacted the selection of planning units incorporated into renewable energy zones (Figure 3) .

Reassessing trade-offs between industries under co-location scenarios resulted in different trade-off curves (Figure 4). Understandably pot fishing experienced less reduction in target obtainment in co-location scenarios, not experiencing any decline until 78% of the potential area was allocated to renewable energy zones, as opposed to 72% when there was no co-location (Figure 4d and Figure 1d). Interestingly *Nephrops*, Scallops and both renewable energy types also experienced less reduction in target obtainment in co-location scenarios, particularly at lower target levels (Figure 4, b & d and Figure 1, b & d). At higher target levels the difference reduced and the maximum targets obtainable were the same in both scenarios, reflecting the constraints of the conservation requirements.

4. Discussion

We developed an ocean zoning approach for multiple industries and conservation, and assessed the trade-offs between allocating space to marine renewable energy generation and maintaining fishing value. We found that the trade-offs between fishing and renewable energy were non-linear and that they varied depending on the specific fishery or type of renewable energy. We also found that co-locating some fishing activity within renewable energy zones both significantly reduced the cost of planning solutions and changed the spatial distribution of renewable energy zones.

The difference in the trade-off curves for the individual sectors within each industry the extent to which the competing uses overlap spatially and the variation in spatial heterogeneity in fishing value between the fisheries. The pot fishery, for example, occurs mainly near the coast and has a high level of spatial heterogeneity. The value of the *Nephrops* fishery, on the other hand, is relatively evenly dispersed but restricted to the southern section of the study site, which is also where the largest potential windfarm development area is located. Thus, the extent to which the cost of allocating space to renewable energy can be minimized was greater for the pot fishery than it is for the *Nephrops* fishery.

Here we have traded off two different things, maintaining access to fishing value and providing space for renewable energy generation, whilst ensuring biodiversity goals were achieved in MPAs. For the fishing industry we had data on the spatial variation in value, but for the renewable energy we did not. Whilst the entire area considered for renewable energy has been designated as suitable for development, it is likely that that the energy-generation value of the potential sites will vary spatially, as will the cost of development, and thus that some parts will prove more valuable than others. Such data, where available, could be readily incorporated into our approach and would allow a more accurate prioritization of planning units within renewable energy zones. Indeed this approach can be adapted to suit the planning goals and the data available. If planners had an energy generation target for renewable energy developments, for example, and data were available on the energy generation potential of the various sites for the different sectors (wind, tidal, wave), this approach could be used to explore trade-offs between how the energy is generated (what combination of sectors) and the cost to the fishing industry. Or, if data were available on the potential revenue from renewable energy generation then planners could use this approach to explore trade-offs between opportunity costs and existing costs (fishing value lost) of planning solutions.

Planners may be interested in minimizing the total cost of planning solutions, but they may also wish to equitably spread the impact across industry sectors, avoiding, for example, a single fishery incurring all the costs associated with the development of a wind farm. Understanding how the individual sectors are affected can help identify where the most potential conflict will be, inform where to focus stakeholder discussion, and contribute to mitigation strategies.

One possible mitigation strategy, when uses are combatable, is facilitating and maximizing co-location opportunities between interests competing for space. Co-location of biodiversity conservation and fishing is common, as very few no-take MPAs exist (Wood et al., 2008). Within our scenarios, two of the MPA types allowed some forms of fishing. We explored another type of co-location, between fisheries and renewable energy.

Currently, offshore wind farms generally become exclusion zones for fishing, particularly fishing with mobile gear, as spacing between turbines is normally inadequate for fishers to safely deploy their gear (Mackinson et al., 2006). A growing body of research exists, however, on the potential benefits of fisheries and renewable energy co-location, particularly with static gear (Hooper and Austen, 2014; Skerritt et al., 2012). Evidence suggests that commercially important species gather near wind turbines and that turbines could provide suitable habitat for species such as the brown crab (*Cancer pagurus*) (Hooper and Austen, 2014). Mechanisms have been suggested for enhancing the artificial reef effects of turbines, such as deploying additional rock armouring around the base to increase the amount of suitable habitat, which would not only support co-location but could lead to these sites providing added fisheries benefits (Bunker, 2004; Hooper and Austen, 2014). There is also great interest in the potential to co-locate offshore wind farms with offshore aquaculture (Michler-Cieluch and Krause, 2008), another rapidly expanding marine industry, which is expected to become increasingly important in meeting the rising human demand for animal protein (Marra, 2005). Our approach could be adapted to also zone for different types of aquaculture, or any other ocean use.

Here, we show that co-location could significantly reduce the cost of planning solutions, even at relatively low co-location levels (25% of previous value to the fishery). Co-location proportionally reduced the cost of locating renewable energy sites in areas where pot fishing occurs and allowed for some of the pot-fishing target to be met in renewable energy zones. Doing so impacted the selection of planning units for the renewable energy zones, increasing the amount of pot-fishing SAP within the renewable energy zones and 'freeing up' other areas, according to their cost, which allowed more of the other fisheries SAP to remain within the fishing zone. Doing so meant that even fisheries that weren't co-located experienced significant cost reductions under co-location scenarios, which demonstrates the need to consider indirect effects of co-location when weighting up potential benefits and costs.

We also found that co-location alters the location of priority areas for renewable energy sites, such that optimal location of renewable energy could depend heavily on how much, if any, co-location occurs. This stresses the need for multi-industry marine planning that considers co-location possibilities from the outset. It also highlights the importance of further research on the benefits, and possible drawbacks (e.g. noise), renewable generation has on different species.

There are costs involved in co-location, which we did not consider. There would be costs associated with adapting renewable energy infrastructure and site designs, such as adding additional rock armouring or increasing turbine spacing. There will also be inevitable initial disturbances (e.g., construction) that could delay the ability of the site to provide fisheries benefits (delayed zone effectiveness). Given available data, these costs could be considered in our zoning approach.

Transparent trade-off analyses are essential for improving the efficiency and defensibility of planning decisions (White *et al*. 2012). Often trade-offs are not clearly addressed, go unrealized or are inadequately evaluated. This is particularly the case in the marine environment where planning and management responsibilities tend to be spread over multiple government departments, who often have conflicting objectives, and between whom collaboration and communication can be poor (Kittinger et al., 2011; Yates et al., 2013). To enable optimal space allocation, ocean zoning processes will need to incorporate simultaneous consideration of all uses of ocean space and planning will have to span all relevant government departments. By explicitly quantifying trade-offs, our approach could help inform and rationalize debates over planning options.

Trade-off analyses help to communicate planning options with stakeholders. Stakeholders are an essential aspect of marine spatial planning and should be incorporated into all stages of the planning process (Pomeroy and Douvere, 2008). One of the many advantages of using Marxan is the ability to generate multiple planning solutions for every scenario. Planners can present a range of zoning configurations, from one scenario or several, and get feedback from stakeholders on their preferences and concerns (Klein at al. 2008, Game et al., 2011).

5. Conclusion

As human use of the marine environment expands and intensifies, the need to minimize conflict and maximize spatial efficacy will grow. Decision makers require guidance on how to zone the ocean for multiple uses in a way that achieves both ecological and socio-economic goals. Our approach facilitates the development of ocean zoning solutions that optimizes the location of MPAs and emerging industries, whilst minimizing impacts on existing sectors. The approach allows the transparent exploration of trade-offs, uses a free planning tool, and is readily adaptable to different planning scenarios. The use of this approach should assist ocean zoning and marine spatial planning processes to identify efficient and defensible solutions to multi-industry spatial conflicts.

Supporting Information

Additional supporting information may be found on the online version of this article: figure S1 Location map of Northern Ireland showing the existing MPAs and the potential renewable energy zones, Table S2 list of conservation feature, and Figure S3 showing trade-offs at different conservation targets.

Acknowledgments

Our thanks to Dr Sylvaine Giakoumi, Dr Beverly Clarke and Dr Thomas Smyth, for reviewing earlier versions of the manuscript and providing invaluable feedback. Our thanks also to two anonymous reviewers for their comments and suggestions. KLY was supported by a Department of Employment and Learning PhD studentship and an Endeavour award (2967_2012). CJK is supported by an ARC Postdoctoral Fellowship (DP110102153). This research was also supported by the ARC Centre of Excellence for Environmental Decisions, University of Queensland.

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Table 1. Description of the seven zones considered in our zoning analysis, including costs and targets.

Zone type	Zone	Main purpose(s)	Activities excluded	Associated targets
MPA	Reserves	Biodiversity conservation Reference sites	All fishing All sea bed development *	15 - 25 % of each conservation feature, across the three MPA types 5 % of each conservation feature contained within a reserve 10 % of the main scallop grounds, across the three MPA types 5 % of the main scallop grounds within scallop management areas
	Conservation	Biodiversity conservation	All fishing, except static gear All sea bed development*	
	Scallop management	Fisheries management Biodiversity conservation	Benthic trawl and dredge fishing All sea bed development*	
Renewable energy	Wind	Renewable energy generation	All fishing (initially)	30 - 82 % of the total suitable area
	Tidal			
Fisheries	Fishing	Fishing	Renewable energy development	80 - 94 % of total SAP (fishing value) for each of the main fisheries
	Aquaculture	Aquaculture	All fishing All sea bed development *	none, existing areas fixed in

* such as laying cables or building renewable energy structures

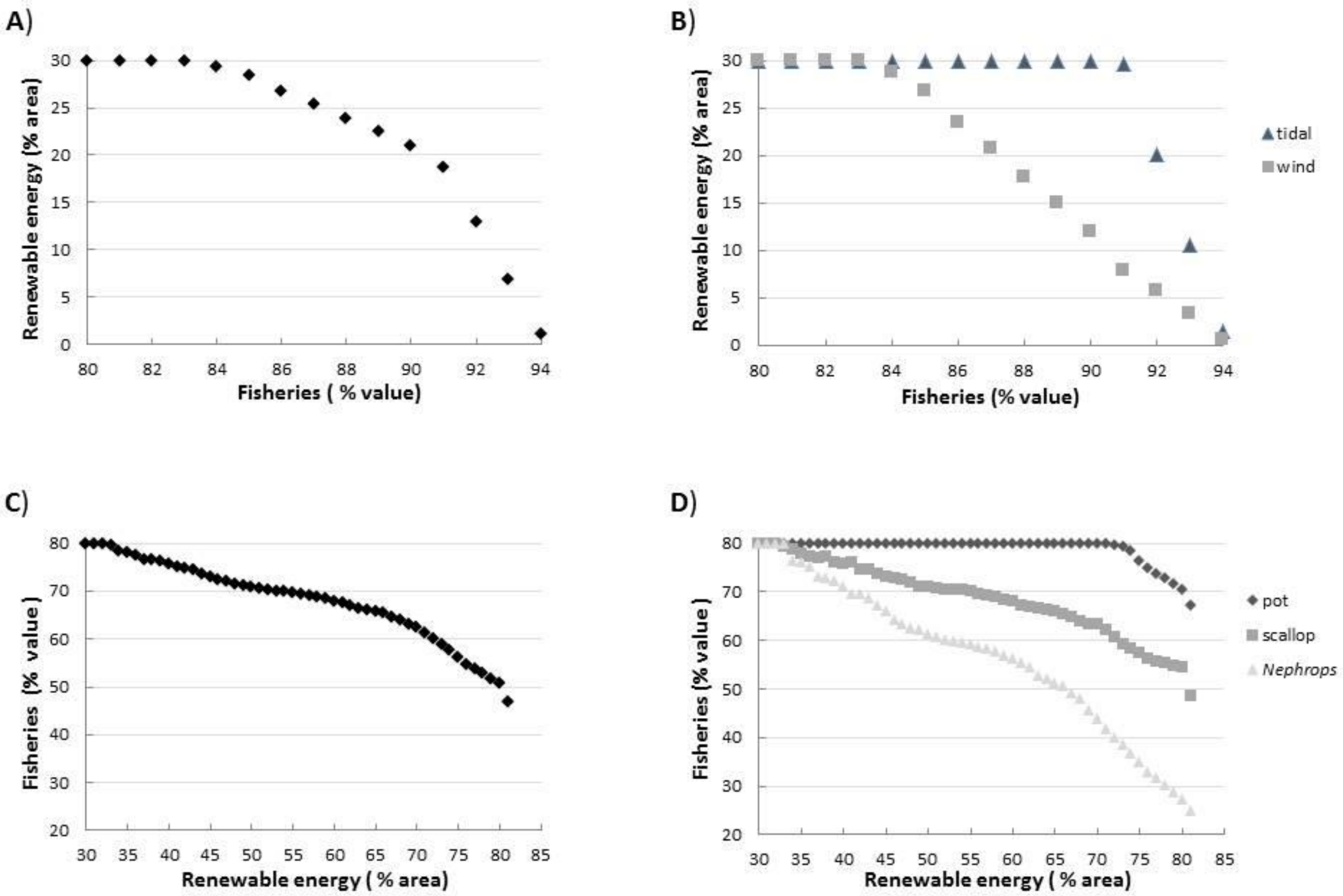


Figure 1. Trade-offs made between achieving fisheries and renewable energy targets. A) overall renewable energy versus fishing value, B) sector specific renewable energy versus fishing value, C) overall fisheries value versus renewable energy, D) sector specific fisheries value versus renewable energy. Initial targets for fisheries (80% of fishing value) and renewable energy (30% of the potential area) were increased iteratively and the impact on the other industries target obtainment was observed. Results shown are for the best solution to each scenario. Conservation targets were achieved in all scenarios.

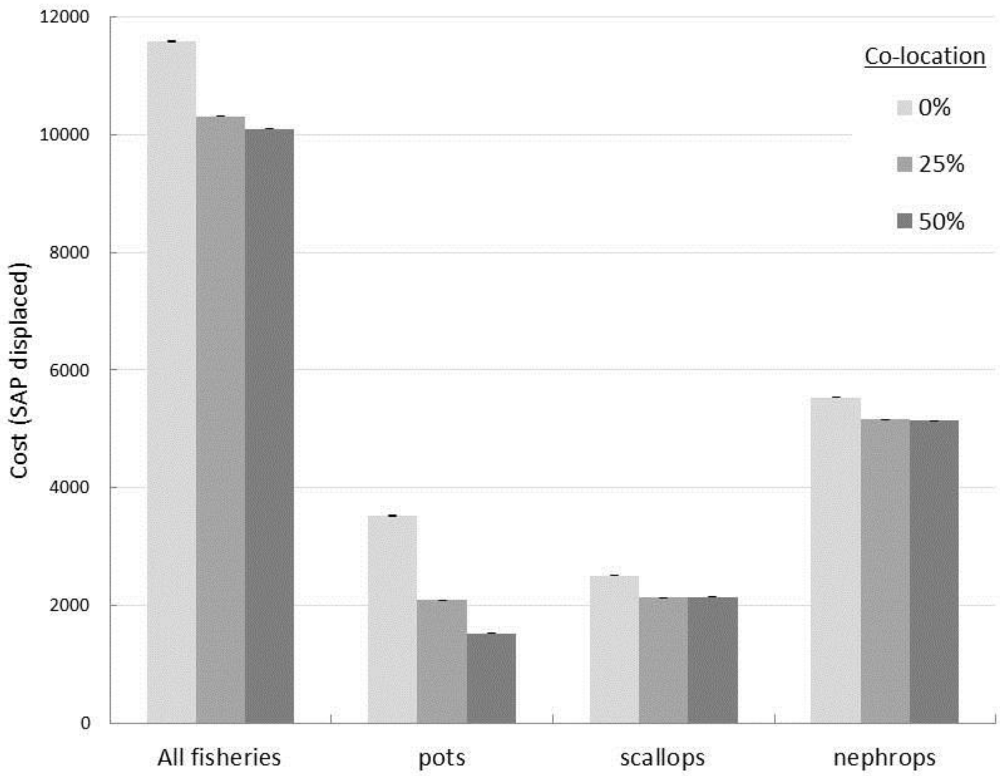


Figure 2. Cost of marine zoning solutions that allow for 0, 25 or 50% co-location of pot fishing within renewable energy-development sites. Cost is the mean SAP displaced (fishing value lost) across the ten best solutions for each scenario and is shown for the entire fleet (all fisheries) and separately for each of the three main fisheries. All targets were met in each scenario. Standard error bars are included.

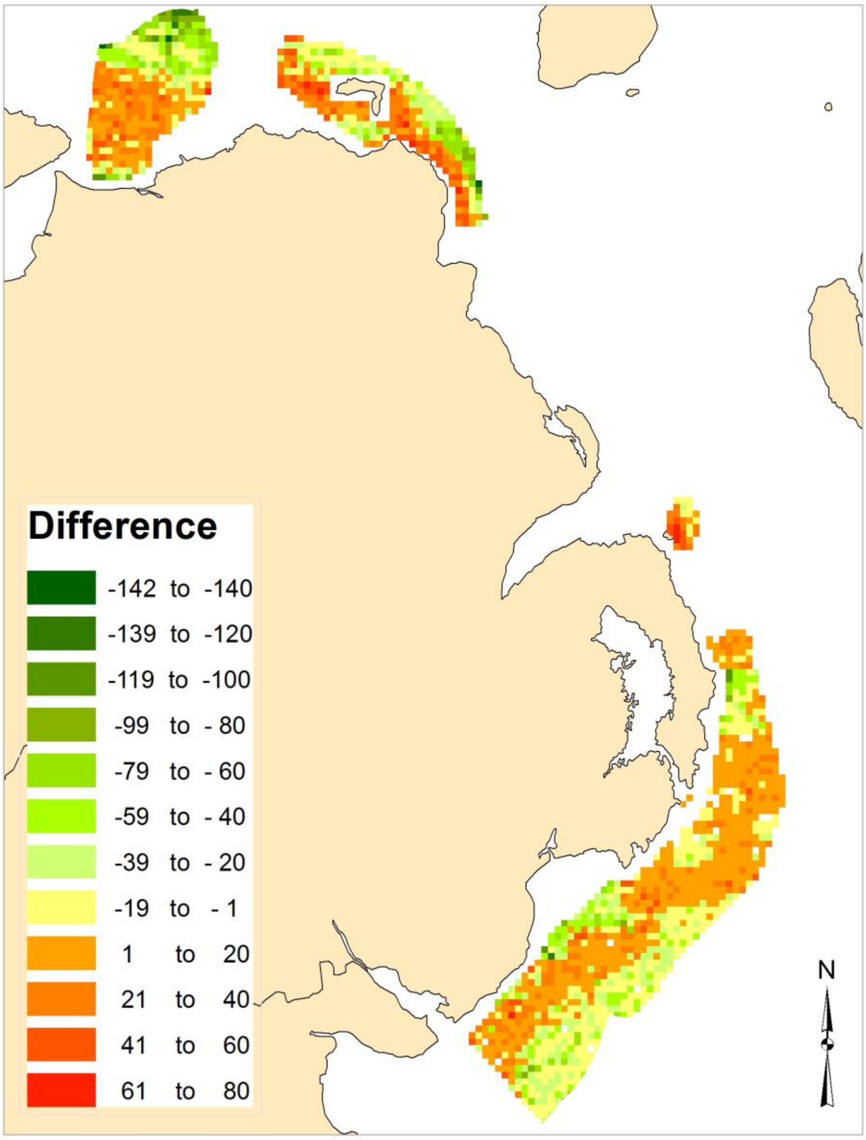


Figure 3. Difference maps showing how co-location affects the selection frequency of planning units within renewable energy zones. Planning unit selection frequency is the number of times a planning unit was incorporated into one of the 200 planning solutions. The maps show the difference in selection frequency between a standard scenario (80% fisheries target, 30% renewables, 15% conservation) without colocation and the same scenario with 25% colocation of pot fishing within renewable energy zones.

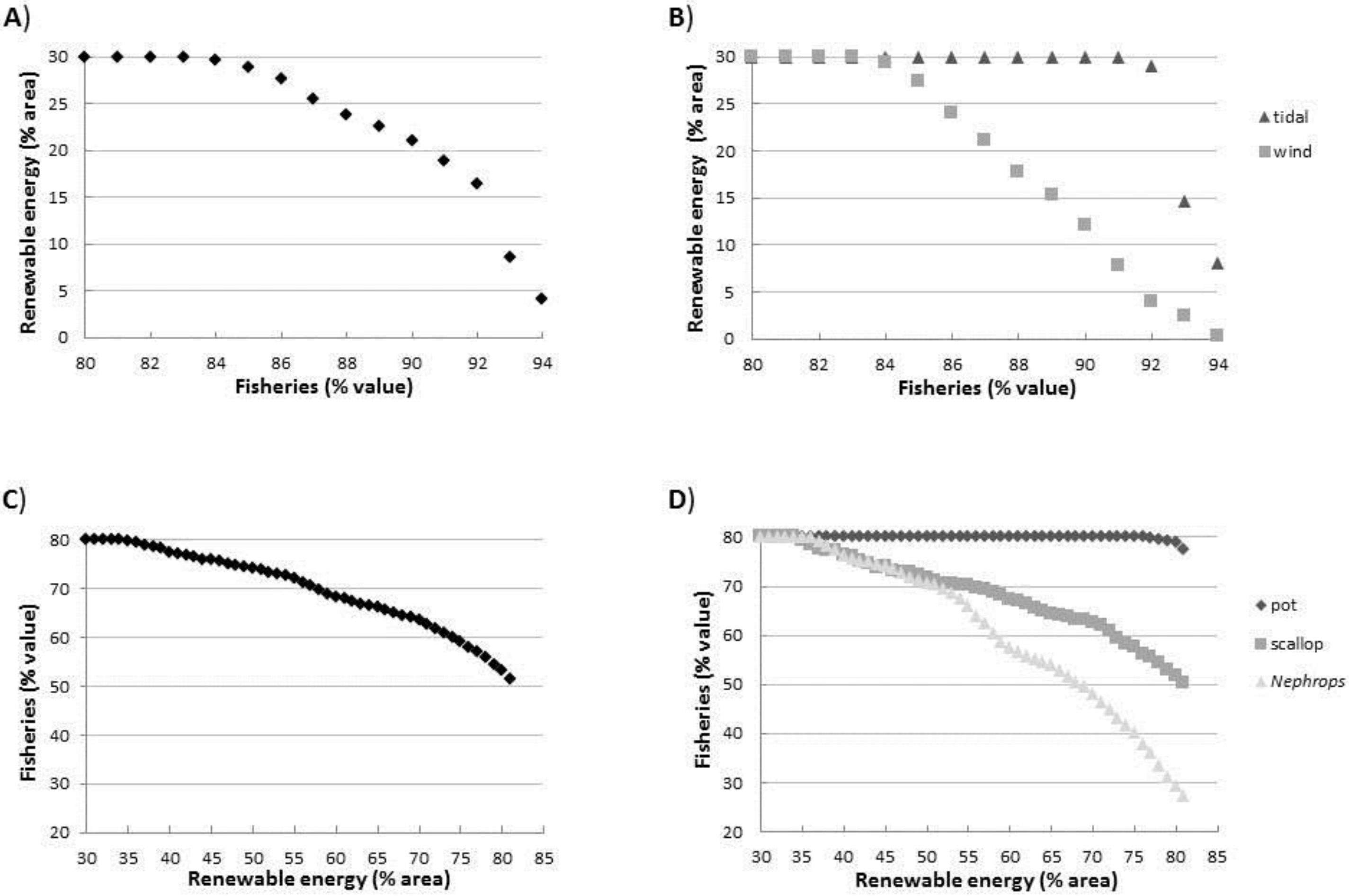
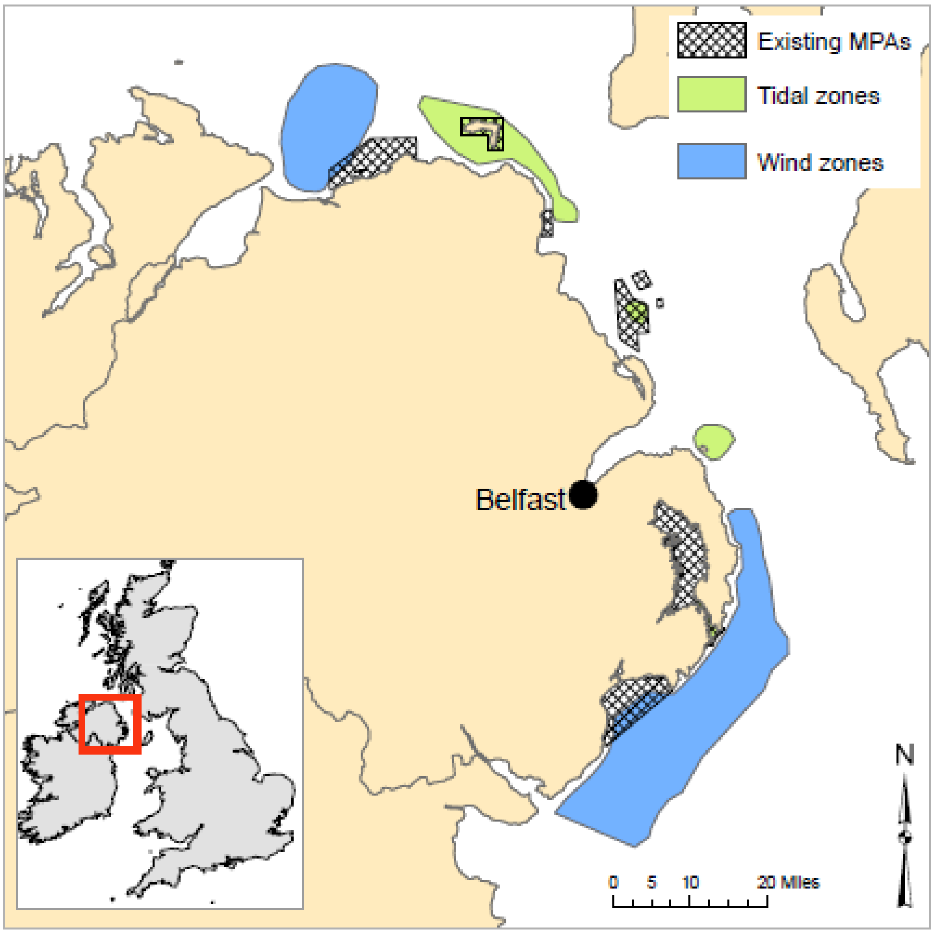


Figure 4. Trade-offs made between achieving fisheries and renewable energy targets under co-location scenarios. A) overall renewable energy versus fishing value, B) sector specific renewable energy versus fishing value, C) overall fisheries value versus renewable energy, D) sector specific fisheries value versus renewable energy. Initial targets for fisheries (80% of fishing value) and renewable energy (30% of the potential area) were increased iteratively and the impact on the other industries target obtainment was observed. Results shown are for the best (least cost) solution to each scenario. Conservation targets were achieved in all scenarios.

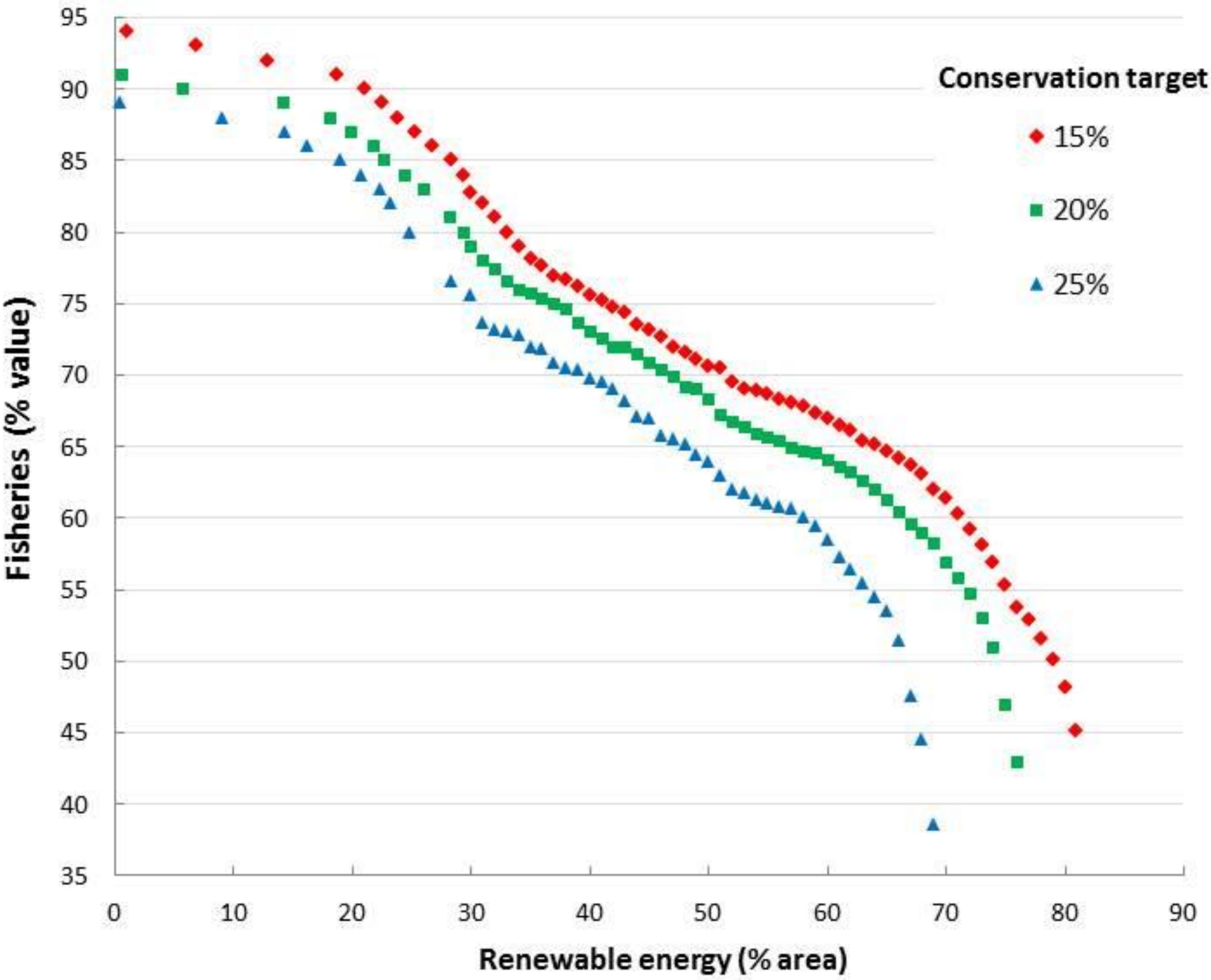


Supplementary Figure S1. Map showing the location of Northern Ireland, the existing MPAs and the potential renewable energy zones.

Supplementary table S2. List of conservation features and surrogates.

1 Depth ≤ 1m
2 Depth ≤ 10m
3 Depth ≤ 20m
4 Depth ≤ 50m
5 Depth ≤ 100m
6 Depth ≤ 500m
7 Rock
8 Gravel
9 Sand bank
10 *Zostera* Beds
11 Sea Pen and burrowing mega fauna
12 Maerl Beds
13 *Modiolus Modiolus*
14 Atlantic Slope rock or reef
15 Atlantic Slope sand and muddy sand
16 Deep Circalittoral Seabed
17 High energy Circalittoral seabed
18 High energy Infralittoral seabed
19 Low energy Circalittoral seabed
20 Low energy Infralittoral seabed
21 Moderate energy Circalittoral seabed
22 Moderate energy Infralittoral seabed
23 Atlantic and Mediterranean high energy infralittoral rock
24 Medium to large boulders and bedrock, dominated by flustra plus tall, often thick, hydroid turf.
25 Thick turf of foliose algae on boulders and cobbles
26 Atlantic and Mediterranean moderate energy infralittoral rock
27 Medium to large boulders, with kelp forest and red foliose algae
28 Thick turf of foliose red algae on large boulders or bedrock
29 Small to medium boulders with turf
30 Silted kelp on low energy infralittoral rock with full salinity
31 Medium to large boulders and bedrock, dominated by flustra plus tall, often thick, hydroid turf
32 Very tide-swept faunal communities on circalittoral rock
33 Sponge communities on deep circalittoral rock
34 Mixed faunal turf communities on circalittoral rock
35 Atlantic and Mediterranean moderate energy circalittoral rock
36 Atlantic and Mediterranean low energy circalittoral rock
37 Atlantic and Mediterranean high energy circalittoral rock
38 Faunal communities on deep moderate energy circalittoral rock
39 Circalittoral rock
40 Brachiopod and ascidian communities on circalittoral rock
41 Faunal communities on deep low energy circalittoral rock
42 Infralittoral coarse sediment
43 Circalittoral coarse sediment
44 Deep circalittoral coarse sediment
45 Infralittoral fine sand or Infralittoral muddy sand

46 Circalittoral fine sand or Circalittoral muddy sand
47 Deep circalittoral sand
48 Infralittoral sandy mud or Infralittoral fine mud
49 Circalittoral sandy mud or Circalittoral fine mud
50 Deep circalittoral mud
51 Infralittoral mixed sediments
52 Circalittoral mixed sediments
53 Deep circalittoral mixed sediments
54 Whiting Nursery
55 Mackerel Nursery
56 Herring Nursery
57 Cod Nursery
58 Angler fish Nursery
59 Plaice Spawning grounds
60 Cod Spawning Grounds



Supplementary figure S3. Trade-offs between achieving a range of fisheries and renewable energy targets at three different conservation targets. Results shown are for the best solution (lowest cost) to each scenario.